SmartHub: a manual wheelchair data extraction and processing device

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INTRODUCTION

Manual wheelchair users utilize their upper body extensively to generate the necessary forces for propulsion, and as a result, they are susceptible to musculoskeletal upper extremity injuries [1]. These biomechanically based injuries are often related to propulsion techniques and individual wheelchair configuration [2,3]. In order to better understand how propulsion metrics such as stroke frequency, stroke length and push force relate to biomechanical injury, it is necessary to collect data that can be used to evaluate these metrics over an extended period of time. Currently, a device known as the SmartWheel, manufactured by Out-Front, can be used in a clinical setting to generate a report summarizing these metrics [4,5]. However, this device has a number of limitations that prevent its use in either long-term studies, or to observe patterns of everyday use outside the clinic. The SmartWheel incorporates a range of different sensors in a standalone wheel that is substituted for standard, original equipment wheelchair wheels when in use. The SmartWheel is also relatively expensive, at a retail cost of $6000.00. In practice, the SmartWheel is limited to use in the clinic because of its cost, its weight relative to a typical spoked wheel, and the need to reconfigure the consumer's wheelchair wheel.

With the objective of overcoming these limitations and designing a reasonably priced device for more widespread use, we have developed a novel device, called the SmartHub. The SmartHub is a low cost (approx. $100.00 for components alone), unobtrusive activity monitor designed to collect, and either store or transmit wheelchair propulsion data. This device is approximately the size of a hockey puck, and consists of a WIFI-enabled microprocessor, nine-axis inertial measurement unit, and rechargeable battery that can be easily attached to any existing, original equipment manual wheelchair wheel. The SmartHub collects a wide range of propulsion characteristics in real-time, which can be utilized to produce the metrics of interest. The SmartHub and the resulting information it produces have the potential to allow the study and evaluation of these metrics over a much greater range of use on a user's existing wheelchair configuration, with the goal of reducing upper extremity injuries for manual wheelchair users.

OBJECTIVES

1. To test of the effectiveness and accuracy of the SmartHub activity monitor
2. To gain an understanding of how clinicians can utilize SmartHub
3. To understand how the SmartHub can provide propulsion technique suggestions

METHODS

Initial Iteration

A previous version of the SmartHub was created by Ryan Letcher, a former Ohio State University graduate student in mechanical engineering. His solution consisted of an Arduino microcontroller, 6-axis inertial measurement unit (IMU) for wheelchair dynamics data, a 9-volt battery, and SD card reader for data transfer. This SmartHub attaches to a wheelchair wheel using tape and must be fixed on the point of rotation (axle location) for accurate data [6].

Figure 1. SmartHub Design 1

Once data is taken and stored locally on the SD card, it is manually transferred to a computer, in which a uniquely developed MATLAB script reads the raw data and outputs propulsion metrics in a visual manner, making it readable for both wheelchair users and clinicians.

However, this design iteration has several limitations. Firstly, the device has no proper fixation method to the wheelchair, currently only tape is used, causing inconsistent placement resulting in inaccurate data collection. Additionally, by using a microcontroller, only one program can be run on the device, limiting flexibility and versatility. Once data is collected, it must be inelegantly transferred manually. Future designs would increase data accuracy, while introducing wireless capability, all encased within a portable, adaptable, and robust housing.

Current Design

The current design upgrades all of the hardware and software utilized in the first iteration. Rather than an Arduino microcontroller, a Linux-based Raspberry Pi Zero W is used as the main processor for software flexibility in addition to on-board wireless capability. Additionally, the 6-axis IMU was upgraded to a 9-axis IMU with a magnetometer, accelerometer, and gyroscope for more accurate data and increased functionality. The 9-volt battery was upgraded with a 1000mAh lithium-ion polymer rechargeable battery for approximately 10 hours of constant use. All of these components are encased within a 3D printed housing that magnetically attaches and detaches to any wheelchair wheel with spokes.

Figure 2. Current SmartHub Design

Table 1. SmartHub Functionality Comparison

Capabilities	SmartHub (Initial Iteration)	SmartHub (Current Iteration)
Accurate	▲	●
Adaptable	✕	●
Portable	▲	●
Connectivity	✕	●

Additionally, due to the nature of the 9-axis IMU, placement of this design relative to the axle has no effect on data accuracy. A unique terminal application as well as web-based graphical user interface (GUI) was developed with Python and HTML for ease of use for both the wheelchair user and clinician. The high-level functional iteration comparisons are shown in Table 1.

Final Design Hardware

The brain of the SmartHub is a Linux-based microprocessor, Raspberry Pi Zero W. At a cost of $5.00, and equipped with friendly general-purpose input output, this small form-factor board allows the SmartHub to store and execute a multitude of programs simultaneously will providing various means of communication to host devices. Included on this board is a micro-SD card reader, which is used as a boot drive and removable storage. Additionally, an OLED screen is used to display informative runtime feedback for both clinicians and wheelchair users.

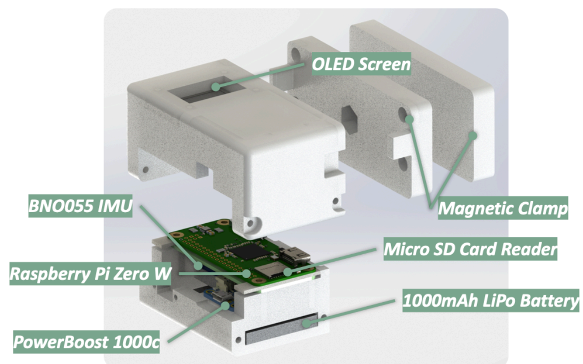

Figure 3. SmartHub CAD Layout

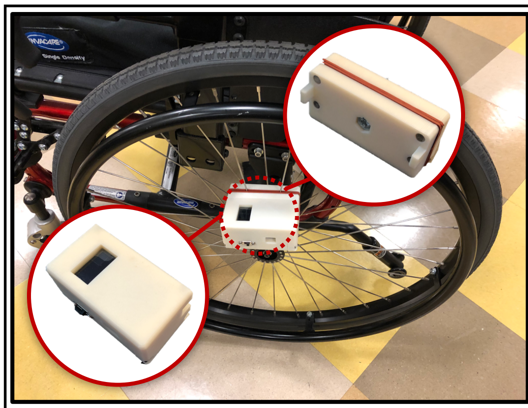

Figure 4. SmartHub on Wheelchair

The main component of the SmartHub is its 9-axis inertial measurement unit, consisting of an accelerometer, gyroscope, and magnetometer. The data streams of all three of these sensors are fused to produce the absolute roll dynamics of the SmartHub. As the SmartHub rotates with the wheel, these roll dynamics are used to calculate the propulsion metrics stated earlier. Additionally, the IMU produces an absolute yaw (heading) data stream, which is utilized to produce the heading dynamics of the wheelchair. Combining the distance and heading, birds-eye, planar trajectory of the wheelchair can be produced with sub-millimeter accuracy. This is used to produce propulsion metrics while collecting data during more naturalistic movement.

These components are housed in a 3D printed, custom design shown in Figure 3 and Figure 4. The design is split into two components, the SmartHub base and the clamping mechanism that is fixed between the spokes, shown in Figure 4. The SmartHub magnetically attaches and detaches to the previously mentioned clamp mechanism for increased flexibility and a safe breakaway design.

Final Design Software

To accommodate the upgraded hardware, an upgrade in software experience was also developed. Instead of utilizing an Arduino microcontroller that is limited to execute one program exclusively, a Raspberry Pi Zero W microprocessor was used, which increases both flexibility and processing power. The Linux-based board also includes Bluetooth and WIFI for wireless connectivity, all within a footprint half the size of the Arduino used initially. The SmartHub is programmed to include both wired and wireless connectivity upon bootup. When plugged in via micro-USB 2.0, the SmartHub bridges the host computers internet access and is able to receive

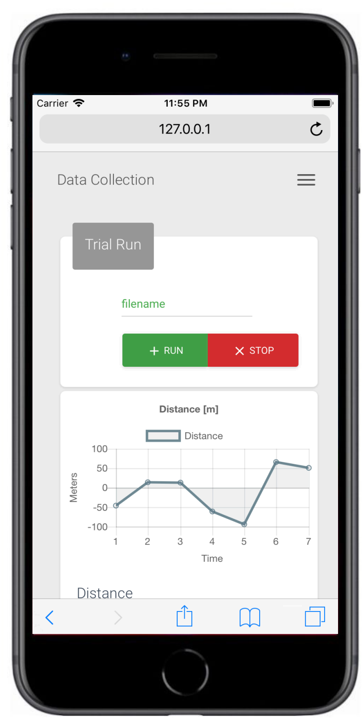

Figure 5. SmartHub Web GUI

updates in addition to communication. Development and the majority of programming was done over this protocol. Additionally, upon bootup, the SmartHub creates and broadcasts its own 802.11b WIFI network. In order to connect to the device, a host computer simply needs to connect to the 'SmartHub' wireless network and enter in proper credentials. This peer to peer (P2P) method is robust and encrypted for seamless and secure data transfer.

Once connected either over USB or over WIFI, a host computer can connect with a terminal application via SSH (secure shell). This allows a remote machine to securely interact with the SmartHub, but only if both the machine and SmartHub are on the same network. Additionally, upon bootup, the SmartHub are on the same network. Additionally, upon bootup, the SmartHub hosts a uniquely developed webpage for graphical interaction. This allows for ease of use for both wheelchair users and clinicians who are not as computer savvy while providing a friendly interface. Because the GUI is web-based, any platform (iOS, Android, OSX, Windows) can connect and interact with the SmartHub. For versatility and ubiquity, Python was used for all SmartHub code. Programs for data collection, HTML webpage hosting, and post-processing were all built from the ground up and by using a standard language, code fluidity is maximized for future development.

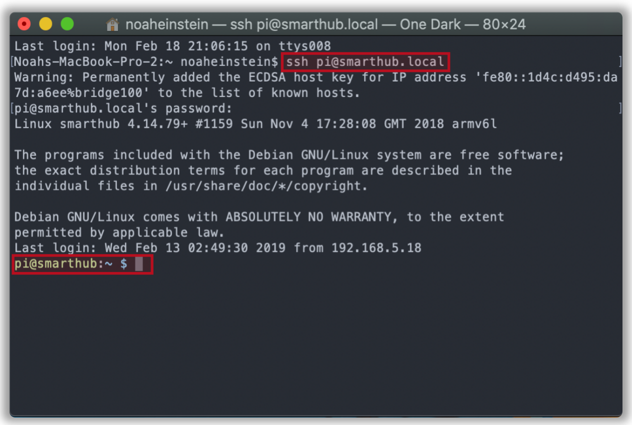

Figure 6. SmartHub Command-Line

Because the entirety of the source code, including the OS image, is comprehensive, a robust version control infrastructure was created to ensure optimal code tracking and user modification of all code. Additionally, this version control system allows for roll-back ability in the case of broken or damaged code and the ability to assign simultaneous working tasks for future developers. All SmartHub code is hosted on a private repository on GitHub.

Testing Protocol

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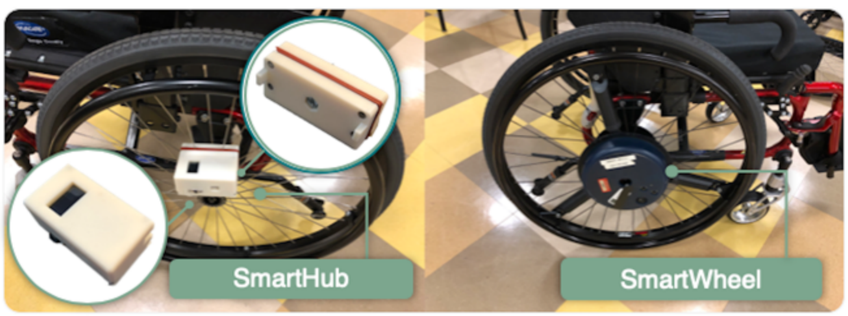

Figure 7. Testing Setup

calculated in a manner that relies on knowledge of the type of surface material (carpet, tile, wood, etc.). In order to validate the SmartHub and its output, we utilized a specific wheelchair configuration- a manual wheelchair (Invacare TRA) with one rear wheel configured as a SmartWheel and the other rear wheel configured as a standard wheelchair wheel with the SmartHub attached, shown in Figure 7. We conducted three validation tests: 1) ten meters on tile; 2) ten meters on carpet; and a figure-8 test on tile. Because the SmartHub can calculate directional heading, in addition to validation testing with the SmartWheel, the SmartHub was also tested in the standard Wheelchair Skills Program (WSP) [7], which involves a sequence of specific activities that are used to evaluate wheelchair users' effectiveness and abilities. These activities include maneuvering on inclined ramps, figure-8 movements on a flat surface, and oval track distance tests. To test validity of heading, subjects conducted the figure-8 protocol of the WSP.

Data Analysis

In order to compare the SmartHub and the SmartWheel during the 10-meter distance test, a unique python script was developed to create a report post-testing. The script reads in both the SmartHub and SmartWheel raw data, time syncs the two data streams, and outputs a summary report including statistics to evaluate device-to-device accuracy. Additionally, a separate SmartHub report, shown in Figure 8, is generated locally on the device. The validation data is then compiled to produce an overall comparison summary for evaluation purposes. Sixty unique, clinical care,

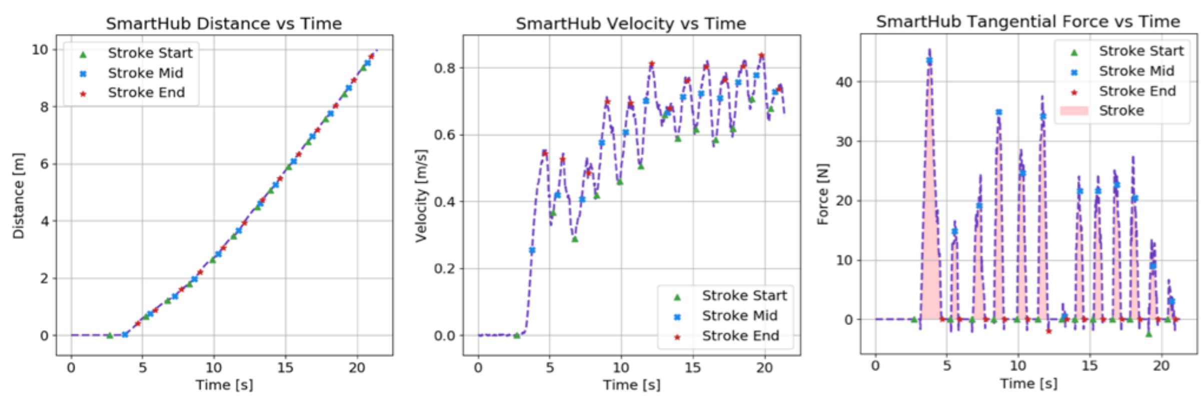

Figure 8. 10-Meter Test (Tile)

10-meter trials were conducted (30 on tile surface and 30 on carpeted surface). To compare the SmartHub against the SmartWheel, data were compiled and analyzed at stroke occurrences. Metrics examined included number of strokes, distance traveled, average stroke velocity, stroke frequency, and peak tangential force. Each trial produced six to seven strokes resulting in approximately 450 unique data points for validation.

RESULTS

The percent error for each metric is calculated as the average (*avg*) of all absolute values (*abs*) of the difference in the SmartWheel data point and SmartHub data point divided by the SmartWheel data point. The preliminary data show that the SmartHub is more accurate on the tile surface than the carpeted surface, however, the relative error with respect to individual metrics appears consistent regardless of surface type. Average percent error of the SmartHub data as compared to the SmartWheel for all validation trials was then calculated, shown in Equation 1, over all stroke locations and represented in Table 2.

Table 2. 10-Meter SmartHub Error

Metric	Percent Error [%]	
	Tile	Carpet
Distance	3.41	3.32
Stroke Length	7.05	9.09
Average Stroke Velocity	8.22	8.5
Average Stroke Frequency	4.91	5.47
Peak Tangential Force	16.74	22.98

$$Percent\ Error_{metric} = avg\left[\frac{abs(SmartWheel_{metric} - SmartHub_{metric})}{SmartWheel_{metric}} * 100\right] \qquad [1]$$

The data for distance, velocity and tangential force for a test subject 10-meter tile test are shown in Figure 8. Included in this figure is the distance traveled over time (clipped at ten meters), the velocity profile of the SmartHub, and tangential force curve from the SmartHub over time. The data for distance, heading, and path of travel for a figure-8 test are shown in Figure 9. Included in this figure are three plots- increasing distance over time, wheelchair heading over time, and the resulting vectorized trajectory of the wheelchair from a birds-eye perspective.

All data displayed in Figure 9 were collected from a consented subject covered under The Ohio State University IRB protocol no. 20170302.

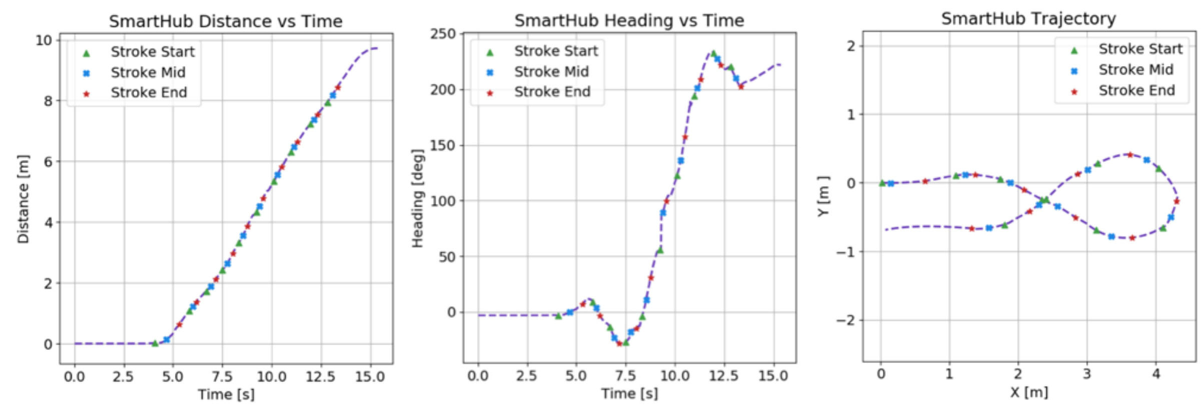

Figure 9. Figure-8 Test (Tile)

DISCUSSION

The ten-meter validation trials demonstrate that the SmartHub is able to produce relevant metrics accurately against the SmartWheel while significantly improving portability and adaptability. Additionally, the figure-8 tests demonstrate the that SmartHub is able to calculate the trajectory of wheelchairs with sub-millimeter accuracy. Combining force and stroke data with trajectory data, the SmartHub allows end-users and clinicians to understand everyday propulsion productivity in a simple and effective manner. However, one advantage that the SmartWheel has compared to the SmartHub, is its ability to more accurately calculate tangential and normal force. This is due to the fact that the SmartWheel utilizes strain gauges to measure the force in three axes. In contrast, the SmartHub relies on motion data, resulting in less accurate tangential force data.

Aside from mechanical attachments to produce tangential and normal force data, the error in tangential force could be reduced by performing static and dynamic calibration tests to more accurately measure force relative to the SmartWheel. The importance of this data relies heavily on trends rather than highly accurate data. Through validation tests, the SmartHub demonstrates highly similar trends in tangential force while being a relatively accurate predictor of propulsion techniques for clinicians.

The current study focused heavily on highly controlled scenarios- ten-meter distance tests on both tile and carpet. Additional data will be collected and analyzed throughout the wheelchair skills test, to help clinicians accurately identify wheelchair user characteristics.

CONCLUSION

While the SmartWheel is currently suited for clinical settings, the SmartHub has the potential for use in any range of settings, due to its portability, hardware adaptability and increased functionality for the wheelchair user. As such, it can be used to provide clinicians and users with a broad understanding of propulsion techniques and overall wheelchair use in a wide range of settings. Manual wheelchair users could benefit from accurate propulsion metrics gathered in a simple, unobtrusive manner. Additionally, because the SmartHub is an attachment rather than a standalone wheel, subjects noted the comfortability of using their personal wheels rather than the cumbersome SmartWheel to collect data.

This study was the first case study to demonstrate the feasibility and usability of the SmartHub for manual wheelchair users in addition to establishing the accuracy of the SmartHub. The SmartHub is a tool that can be utilized to provide a range of insights and ultimately optimize healthcare delivery and outcomes for many manual wheelchair users.

FUTURE WORK

Current data includes the ten-meter, figure-8, and the range of the wheelchair skills tests. Future studies are planned that will be conducted in everyday, out of clinic general use to gather data on real-world manual wheelchair propulsion techniques. Furthermore, additional research personnel will be used to investigate and validate inter-subject variation. As stated earlier, future calibration tests will be performed to more accurately produce tangential force data. Future studies are also planned to utilize SmartHub data with other musculoskeletal biomechanics to understand upper extremity usage during propulsion.

Additionally, the SmartHub local and remote software will be updated based on initial usability evaluations and tested by a larger user group. Focus groups will be conducted to obtain feedback from clinicians and end-users regarding use of the accompanying SmartHub application and its output. After an optimized user interface is developed, the SmartHub device and application will be further tested by clinicians and manual wheelchair users in both every day and clinical settings.

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